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Anomalous Cosmic Rays

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Abstract. Anomalous cosmic rays (ACRs) first started showing up in observations 40 years ago. Within a few years a paradigm was developed to explain their origin: they begin their life as interstellar neutral atoms that drift into the heliosphere, become singly ionized by charge-exchange with a solar wind ion or by photoionization, are picked up by the expanding solar wind, and accelerated to the observed energies by diffusive shock acceleration at the solar wind termination shock. This paradigm became widely accepted and withstood the tests of further observations until 16 December 2004, when Voyager 1 crossed the termination shock and didn't find their source. In August 2007, Voyager 2 crossed the termination shock and also did not find the source location of ACRs. Clearly, the source location was not at the termination shock where the two Voyagers crossed. Alternative models have been proposed with acceleration elsewhere on the shock or by other acceleration processes in the heliosheath. We discuss the latest observations of ACRs from the Voyager spacecraft and hopefully shed more light on this ongoing puzzle.

Keywords: cosmic rays, anomalous cosmic rays, solar wind termination shock.
PACS: 96.50.Ek, 96.50.Pw, 96.50.S-, 96.50.sh, 96.50.Vg, 96.50.Xy, 96.50.Ya.

BACKGROUND

The anomalous, flat energy spectrum of cosmic ray helium below about 100 MeV/nucleon was first noticed by Garcia-Munoz et al. [1] in data taken in 1972. This was the first indication that something new was occurring. Immediately thereafter, Hovestadt et al. [2] noticed an anomalous bump in the oxygen spectrum between 2 and 8.5 MeV/nucleon in data also taken that same year. McDonald et al. [3] made measurements on Pioneer 10 from 1972-1973 of carbon, nitrogen and oxygen and found the O/C and N/C abundance ratios were not the same as seen in galactic cosmic rays. They argued "… this is most likely a new extrasolar component of cosmic rays". In his rapporteur talk at the 1973 International Cosmic Ray Conference in Denver, Bill Webber noted "Not only do these data agree, which is in itself remarkable, but they show a spectral feature at ~4 MeV/nuc for carbon and oxygen that is not present for He", and went on to say "The spectral feature is most puzzling and if confirmed by other measurements, may represent the first observation of a truly new component at low energies – the origin of which can only be speculated at present" [4].

In 1974 Fisk et al. [5] proposed that these are ionized interstellar neutral atoms. A prediction of this model is that these particles are mostly singly ionized, as was later confirmed by Adams et al. [6]. In 1981 diffusive shock acceleration at the solar wind termination shock was proposed as the acceleration mechanism for ACRs by Pesses et al. [7]. This then became the paradigm for anomalous cosmic rays (ACRs) until late in

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2004: ionized interstellar neutral atoms accelerated by diffusive shock acceleration at the solar wind termination shock.

ANOMALOUS COSMIC RAYS CURRENT SITUATION

The Voyager 1 (V1) spacecraft crossed the solar wind termination shock on 16 December 2004, making it possible to search, in-situ, for the acceleration site and mechanism of ACRs. It was found that the energy spectra of ACRs did not unfold to the shape expected from diffusive shock acceleration at the termination shock and thus the acceleration site and mechanism previously proposed was thrown into question [8]. Similarly, the ACR source location was not observed at the location where Voyager 2 (V2) crossed the termination shock in August 2007 [9]. While the acceleration mechanism and source location are still being debated, the ultimate origin of ACRs as interstellar atoms has not been questioned.

Measurements of particle populations in the heliosheath indicate the presence of three different populations of particles: termination shock particles (TSPs), anomalous cosmic rays (ACRs), and galactic cosmic rays [8]. The TSPs appear to come from the nearby termination shock and the intensities are similar at V1 and V2, while the ACRs appear to be accelerated remotely from the two spacecraft.

Recently, the ACR source intensity appears to be higher at V2 by about a factor of two, some of which is due to a decline of the intensity at V1 [10]. We might expect the V2 ACR intensities to be higher than those at V1 because V2 is closer to a possible source region along the flanks [11] or tail of the shock [12]. Other acceleration locations and mechanisms have been proposed, including magnetic reconnection near the heliopause [13, 14] and a pump mechanism that would also be most effective near the heliopause [15].

While the intensities of mid-to-high-energy ACRs at V2 are now higher than at V1, the V2 spectra appear more modulated, as they are less unrolled than the spectra at V1 (see Fig. 4 of [10]), suggesting differences in the rigidity dependence of the diffusion coefficient between the two spacecraft and the sources. To estimate the rigidity dependence of the diffusion coefficient, we have previously superimposed spectra of different species with shifts in intensity and energy until the spectra all aligned [16].

In Figures 1 and 2 we have taken a different approach and plotted intensities vs. time for a reference species and reference energy bin along with intensities from several energy bins from a different species. Assuming the observed intensity changes are due to spatial diffusion, the profiles will align for particles having the same diffusion coefficient. We find that for V1, ACR He with ~11.5 MeV/nuc has the nearly same profile as ACR H with ~35 MeV. ACR O particles with ~3.5 MeV have nearly the same profile as ACR He with ~11.5 MeV/nuc. This implies that an energy per nucleon scaling factor of ~3 per factor of 4 in mass is at work, which implies $K \sim \beta R^{0.66}$ for V1 [16]. At V2 the scaling is similar except the scaling factor is 4.8 per factor of 4 in mass, implying that $K \sim \beta R^{1.3}$ for V2. So, the steeper rigidity dependence at V2 may explain why ACR spectra are more modulated at V2 even though the intensity is higher than those at V1 at higher energies.

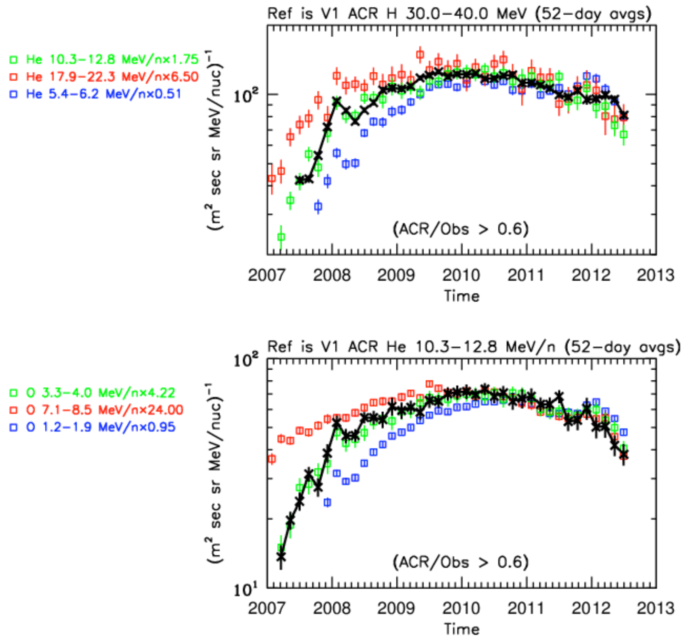

FIGURE 1. (top) Intensities vs. time for ACR H and He at V1 for different energy bins. The profile for ACR He with 10.3-12.8 MeV/nuc matches well the reference profile of ACR H with 30-40 MeV. (bottom) Intensities vs. time for ACR He and O at V1 for different energy bins. The profile for ACR O with 3.3-4.0 MeV/nuc matches well with the reference profile of ACR He with 10.3- 12.8 MeV/nuc. See text for implication.

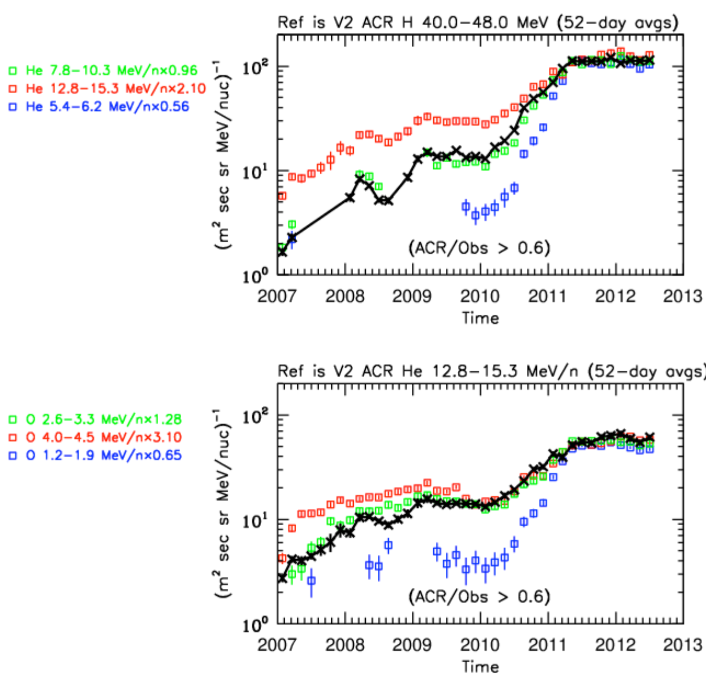

FIGURE 2. (top) Intensities vs. time for ACR H and He at V2 for different energy bins. The profile for ACR He with 7.8-10.3 MeV/nuc matches well the reference profile of ACR H with 40-48 MeV. (bottom) Intensities vs. time for ACR He and O at V2 for different energy bins. The profile for ACR O with 2.6-3.3 MeV/nuc matches well with the reference profile of ACR He with 12.8-15.3 MeV/nuc. See text for implication.

SUMMARY

The ACR V2 intensities in the mid to higher-energy range are now exceeding those at V1, but the V2 spectra are more modulated. This observation supports the theories that the source location is along the flank or tail of the termination shock [11, 12], since V2 is located further from the nose of the heliosphere than is V1. The observation that the V2 ACR spectra appear more modulated than the energy spectra of V1 may be due to a difference in the rigidity dependence of the diffusion coefficient between V2 in the south and its source vs. V1 in the north and its source.

Although the observations are qualitatively consistent with a termination shock source along the flank or tail, other models are also under consideration, including acceleration at hot spots on a turbulent termination shock [17], acceleration at the heliopause due to magnetic reconnection [13, 14], and acceleration by a pump mechanism taking place mostly near the heliopause [15]. Further observation should provide further insight into the nature and location of the source of ACRs.

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REFERENCES

1. Garcia-Munoz, M., G.M. Mason, and J.A. Simpson, *A New Test for Solar Modulation Theory: the 1972 May - July Low-Energy Galactic Cosmic Ray Proton and Helium Spectra.* Astrophys. J. Lett., 1973. **182**: p. L81-L84.
2. Hovestadt, D., et al., *Differential Energy Spectra of Low-Energy (<8.5 MeV Per Nucleon) Heavy Cosmic Rays During Solar Quiet Times.* Phys. Rev. Lett., 1973. **31**: p. 650-653.
3. McDonald, F.B., et al., *The Anomalous Abundance of Cosmic-Ray Nitrogen and Oxygen Nuclei at Low Energies.* Astrophys. J. Lett., 1974. **187**: p. L105-L108.
4. Webber, W.R., *The Energy Spectra of the Cosmic Ray Nucleonic and Electronic Components*, in *Proc. 13th Internat. Cosmic Ray Conf.* 1973: Denver, vol. 5. p. 3568-3614.
5. Fisk, L.A., B. Kozlovsky, and R. Ramaty, *An Interpretation of the Observed Oxygen and Nitrogen Enhancements in Low-Energy Cosmic Rays.* Astrophys. J. Lett., 1974. **190**: p. L35-L38.
6. Adams Jr., J.H., et al., *The charge state of the anomalous component of cosmic rays.* Astrophys. J., 1991. **375**: p. L45-L48.
7. Pesses, M.E., J.R. Jokipii, and D. Eichler, *Cosmic Ray Drift, Shock Wave Acceleration, and the Anomalous Component of Cosmic Rays.* Astrophys. J. Lett., 1981. **246**: p. L85-L89.
8. Stone, E.C., et al., *Voyager 1 Explores the Termination Shock Region and the Heliosheath Beyond.* Science, 2005. **309**: p. 2017-2020.
9. Stone, E.C., et al., *An asymmetric solar wind termination shock.* Nature, 2008. **454**: p. 71-74.
10. Cummings, A.C., et al., *Voyager Observations of Anomalous Cosmic Rays in the Outer Heliosphere* in *Proc. 32nd Internat. Cosmic Ray Conf.* 2011: Beijing, vol. 11. p. 2-5.
11. McComas, D.J. and N.A. Schwadron, *An explanation of the Voyager paradox: Particle acceleration at a blunt termination shock.* Geophysical Research Letters, 2006. **33**: p. L04102.
12. Kóta, J., *Anomalous Cosmic Rays at a Blunt Termination Shock*, in *Proc. 30th Internat. Cosmic Ray Conf.* 2008: Merida, vol. 1. p. 853-856.
13. Drake, J.F., et al., *A Magnetic Reconnection Mechanism for the Generation of Anomalous Cosmic Rays.* The Astrophysical Journal, 2010. **709**: p. 963-974.

14. Lazarian, A. and M. Opher, *A Model of Acceleration of Anomalous Cosmic Rays by Reconnection in the Heliosheath.* The Astrophysical Journal, 2009. **703**: p. 8-21.
15. Fisk, L.A. and G. Gloeckler, *The acceleration of Anomalous Cosmic Rays by stochastic acceleration in the heliosheath.* Advances in Space Research, 2009. **43**: p. 1471-1478.
16. Cummings, A.C., E.C. Stone, and W.R. Webber, *Evidence that the Anomalous Cosmic-Ray Component is Singly-Ionized.* Astrophys. J. Lett., 1984. **287**: p. L99-L103.
17. Jokipii, J.R. and J. Kota, *Particle Acceleration at Shocks: Effects of Spatial Variations Along the Shock Face*, in *American Institute of Physics Conference Series vol. 1039,* 2008. p. 390-396.